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INNOVATIVE THERMAL MANAGEMENT OF FUEL CELL POWER ELECTRONICS

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Abstract

Deep at the heart of any fuel cell system lays a crucial component, the power inverter. The design of this crucial component is a challenge for fuel cell systems due to packaging, thermal and electrical constraints. Unless the inverter is adequately and uniformly cooled it will suffer material degradation and premature failure. The search for a thermally viable inverter design is one of many challenges facing the fuel cell industry today.

In this research effort several cooling techniques were considered such as pin-finned design, “cook-top” serpentine flow field, a “fish bone” fin design, high thermal conductivity graphite foam, heat pipes and aluminum extrusion with expanded metal turbulator. The pin-finned design techniques were evaluated using computational fluid dynamics. In order to enable design engineers to rapidly generate optimum designs two simplified techniques were introduced using the CFD results.

1) Formulas for computing the film coefficient based on spacing, side and configuration are provided for thermal finite element analysis that includes conduction and convection. This technique is an order of magnitude faster than the CFD analysis.

2) Behavioral modeling, an optimization technique imbedded within a feature based parametric CAD system is utilized to automatically size and build the solid model of the pin-finned design. The designer input is the heat that needs to be rejected and the available space. Behavioral modeling generates the design and plots the temperature distribution.

Introduction

Heat rejection from electronic components has become a problem of significant interest due to the continuing reduction in component size and increase in functional performance. It is believed that efficient cooling of these devices is a critical enabling technology for commercialization of HEV & Fuel Cell powered vehicles. The goal of this research effort is to develop a heat exchanger design to efficiently remove heat from the power electronics and reject it into the vehicle's coolant loop with uniform cooling and minimum cost, volume and pressure drop. A number of cooling techniques have recently been examined for heat rejection of power electronics with high heat fluxes.

A heat exchanger with two flat steel plates is examined. The IGBT (insulated gate bipolar transistor) is attached on the top plate and coolant is flowing through the plates. Since there is a single inlet and outlet several variable height

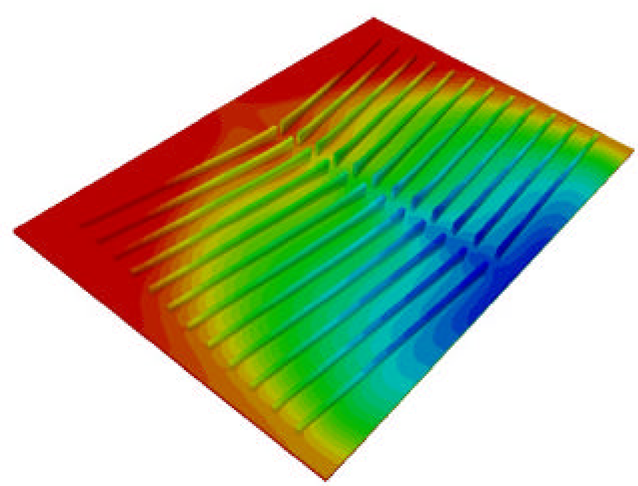

Figure 1 Cooling plate with variable orientation and height Fins

and orientation ribs were considered in order to uniformly direct the flow on the entire surface. The fins were arranged in a "fish bone" orientation as shown in Figure 1. This figure also shows the temperature distribution on the coolant side of the plate with the power electronics. Although the pressure drop, maximum temperature and differential temperature are acceptable the manufacturing cost of this option was very high.

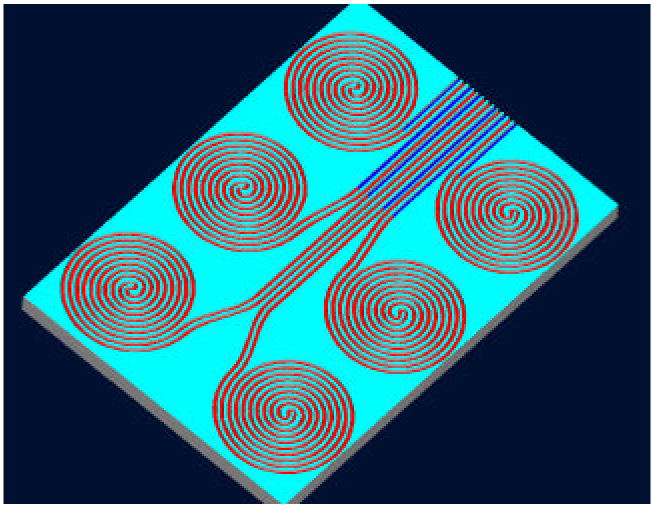

Figure 2 Plate with serpentine flow field channels

In order to deliver uniform cooling to all power electronic modules an alternative serpentine flow field channel design was considered. Parallel paths for inlet and outlet flow channels in a shape of a cook-top were examined. Figure 2 shows the coolant side of the plate with the power electronics. Although the differential temperature was very low and maximum temperature acceptable the pressure drop and the manufacturing cost of this option exceeded the targets.

Other alternative materials also were considered such as high thermal conductivity graphite foams Ref [1]. This unique material is a lightweight, porous graphite foam with exceptionally high thermal conductivity and very efficient thermal energy transfer characteristics. This type of material is dimensionally stable, has low CTE and is not outgassing. It has graphitic-like properties that may not be rugged enough for the harsh automotive environment where reliability and fatigue life targets are very high.

Another potential design alternative is the use of aluminum extruded plates with expanded metal turbulators Ref [2]. This is a low cost, low pressure drop, light weight option with a large surface area of metal in contact with the coolant. Turbulent flow can be achieved in an extruded section by inserting a turbulent generating device (turbulator). The expanded metal turbulators substantially improved heat transfer into the coolant and thus lowered the overall thermal resistance. It appears the maximum temperature target is exceeded due to the limited thermal conductivity of aluminum.

Phase change materials and heat pipes are promising cooling techniques for power electronics. Heat pipes that aid in the transport of heat from the source to the sink through evaporation and condensation are very promising emerging cooling solutions. They use latent heat of vaporization with no temperature change to provide temperature uniformity along the pipe. Phase change materials and heat pipes have not been considered in this effort.

Pin-Finned Design

The most promising design alternative that meets the performance criteria for automotive applications is the pin-finned design Ref [3]. This heat exchanger is composed of to flat plates separated by a set of pins. Figure 3 shows a portion of the Pin-Finned Design with small and large pin

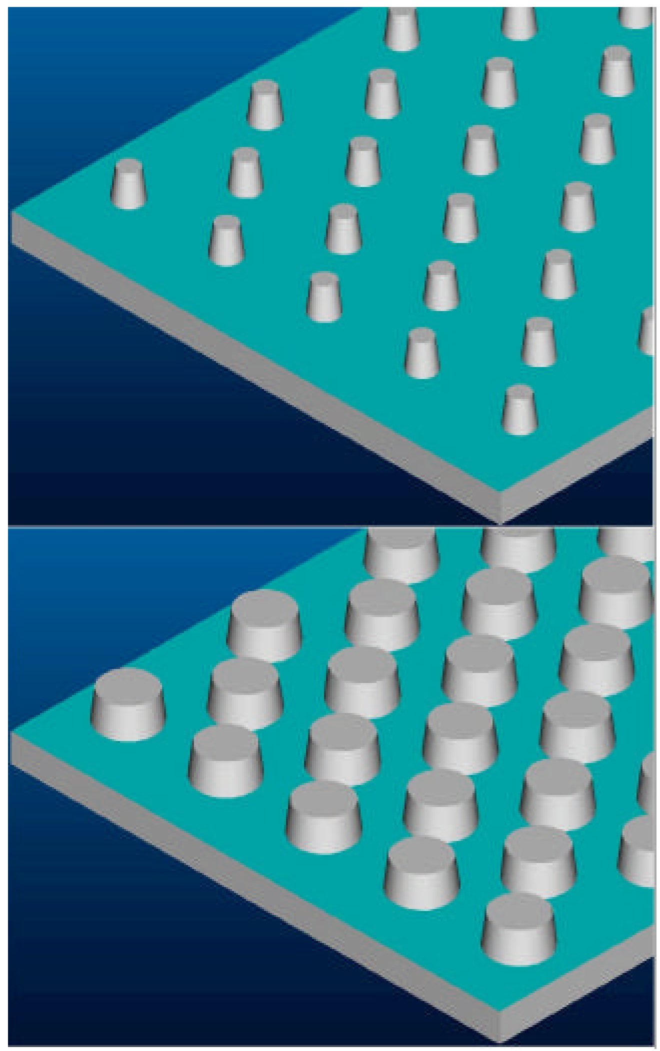

Figure 3 Pin-Finned Design with small and large pin diameter

diameters. For performance validation experimental work is currently under way. This type of work is time consuming and expensive since it requires expensive prototypes and does not provide sufficient information to achieve an optimal design configuration.

A coupled thermal and computational fluid dynamics (CFD) analysis was performed on several designs. Figure 4 shows the particle trace on a portion of a typical pinned finned design. The trace lines are color coded with respect to the particle velocity. Figure 5 shows the temperature distribution on a portion of the same design. This type of analysis is very effective for design evaluation but computationally intensive due to the large number of elements required for an accurate solution. The coupled thermal and computational fluid dynamics analysis is not an efficient method for rapid design alternative evaluation as is required in a rapid new product development environment. In order to address this issue the thermal FEA and behavioral modeling techniques were implemented.

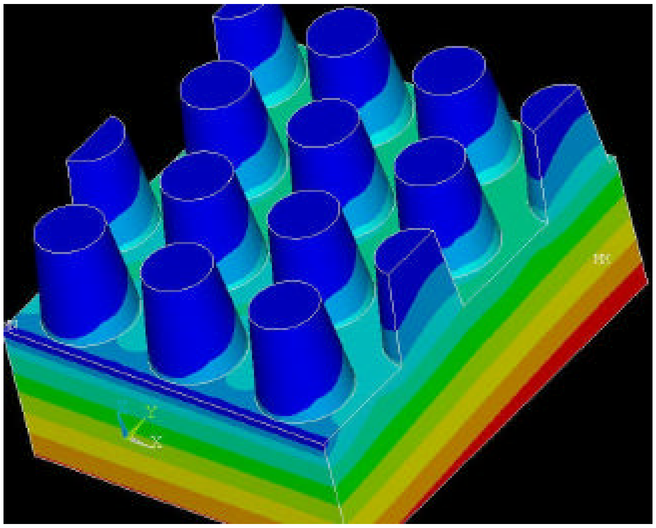

Figure 5 Temperature distribution on a portion of a typical pin-finned design

Thermal Finite Element Analysis

From a CFD analysis in addition to the velocity, pressure and temperature distributions one may obtain the heat transfer coefficient distribution on the interface surfaces between the coolant and the solid.

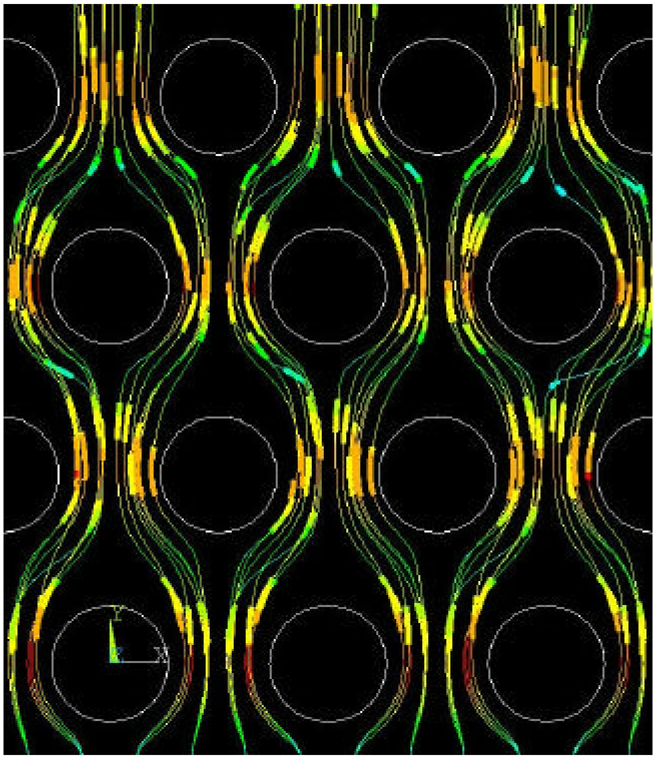

Figure 4 Particle trace on a portion of a typical pinned fined design

The heat transfer coefficient can be correlated to the pin spacing, pin height and pin diameter. A parametric FEA model has been built that utilizes this correlation and computes the heat transfer coefficient based on the geometry and flow rate. The thermal FEA analysis is two orders of magnitude faster than CFD and can run in a couple of minutes on a personal computer. Figure 6 shows the temperature distribution of a typical pin-finned design.

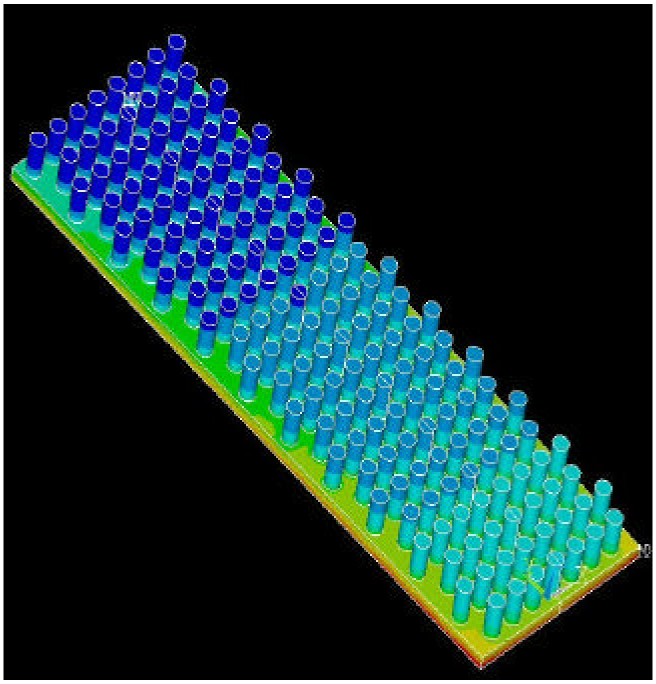

Figure 6 Temperature distribution of a pin-finned design

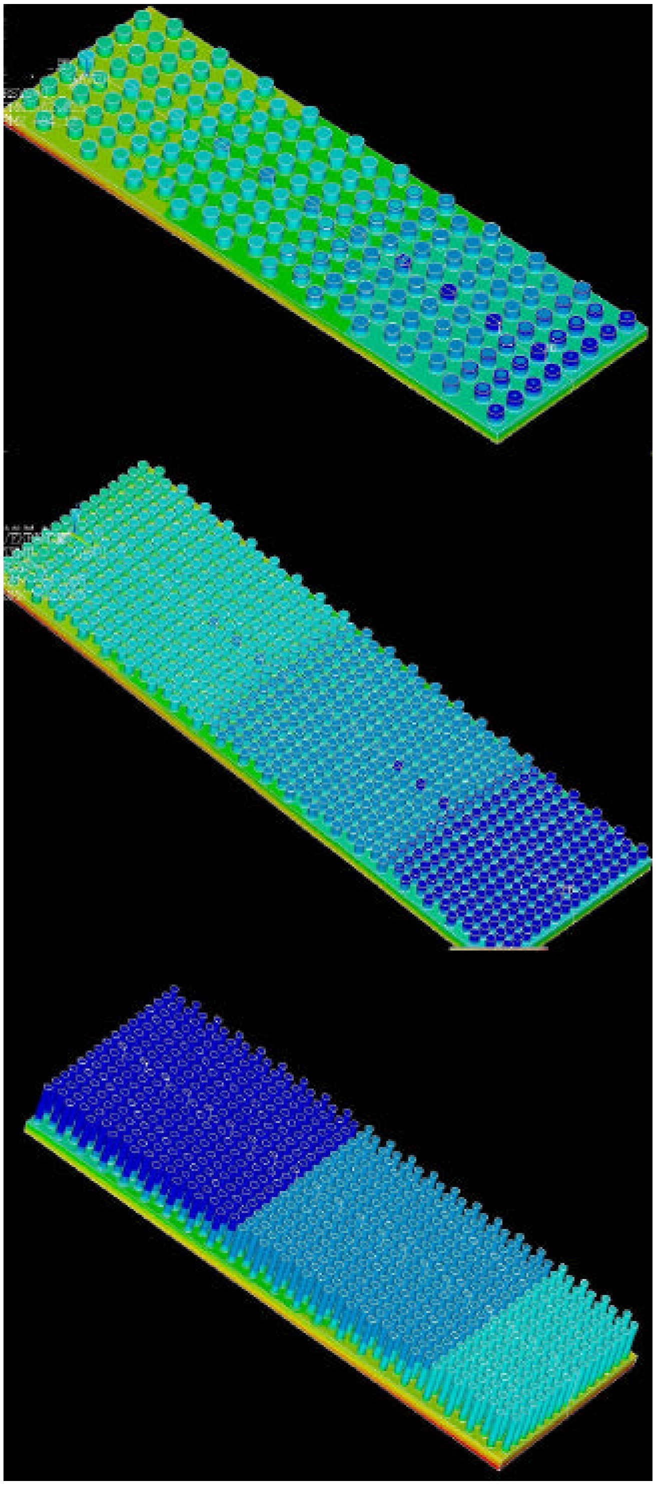

Figure 7 Pin-finned design alternatives

The pin diameter (Dpin), the pin height (hpin), the number of pins in the flow direction (Ny) and the number of pins in the cross flow direction (Nx) were considered as design variables. Figure 7 shows three design alternatives for various values of the design variables.

Classical Formulation

For a preliminary design a classical formulation can be used. Formulas for the heat transfer coefficient for forced convection over staggered pins are derived in Kreith Ref [4] with the basic equations shown below. The first step is to determine the Reynolds number (Re_D) in order to establish whether the flow is laminar, turbulent, or transitional.

$$Re_D = \frac{U_{max} D}{n}$$

where Umax is the maximum coolant velocity through the heat exchanger, D is the pin diameter and ν is the viscosity of the coolant. The maximum velocity is determined from the minimum distance between pins. This value is taken automatically from the parametric solid model geometry.

Depending on the flow regime (Reynolds number) the Nusselt number (Nu) can be determined as follows:

For laminar flow (Re_D <1000) the Nusselt number for staggered pins is:

$$Nu_D = 0.9\, Re_D^{0.4}\, Pr^{0.36}$$

For transitional flow with the ratio of St/Sl < 2, the Nusselt number is:

$$Nu_D = 0.35\left(\frac{St}{Sl}\right)^{0.2} Re_D^{0.6}\, Pr^{0.36}$$

For transitional flow with the ratio of St/Sl >= 2, the Nusselt number is:

$$Nu_D = 0.4\, Re_D^{0.6}\, Pr^{0.36}$$

And for turbulent flow, the Nusselt number is:

$$Nu_D = 0.022\, Re_D^{0.84}\, Pr^{0.36}$$

The heat transfer coefficient (h) is:

$$h = \frac{Nu \times k}{D}$$

The pressure drop (ΔP) across the heat exchanger can be found from:

$$\Delta P = f \frac{rU_{max}^2}{2} N$$

where the friction factor (*f*) is dependent on the Reynolds number, as shown in Ref [4].

Behavior Modeling Implementation of the Classical Formulation

Over the last two decades the introduction of feature based parametric solid modeling CAD systems have greatly increased the productivity of designers. In the last four years PTC's Behavior Modeling Module has extended the CAD associativity to the analysis environment. Geometric features such as cuts, rounds, holes etc. have been part of the regeneration tree of the feature-based systems. Behavior modeling introduced the concept of analysis and optimization features. In other words the weight of a component, its natural frequency or its heat rejection capacity represent typical analysis features that regenerate/update when design variables have changed. The automatic update of the values of the analysis features provides an immediate feedback to the designer and identifies quickly the effect of design changes on the response attributes of the design. The "optimization features" automate an optimization design study within the CAD environment.

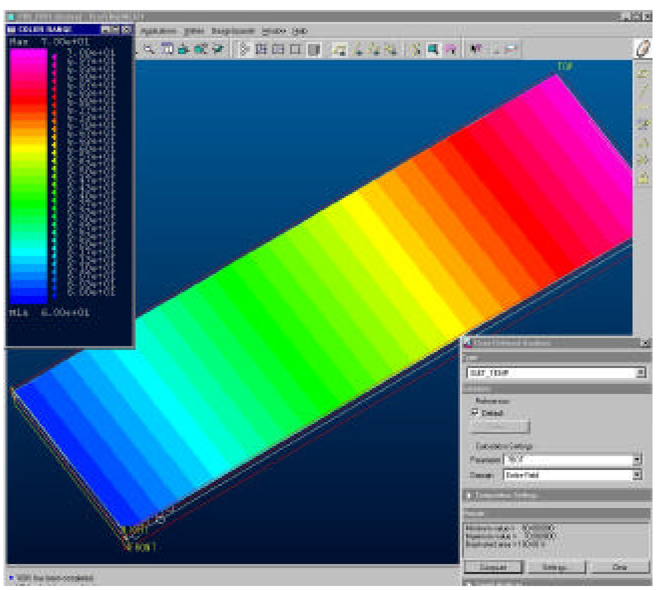

Figure 8 Temperature Distribution within the CAD Environment

In our pin-fin heat exchanger design the number of fins in the x and y directions, height, diameter and the slope of the pins are typical design variables. Several analysis features that compute the flow area between the pins, the surface and the distance between the pin's centroid and the IGBT

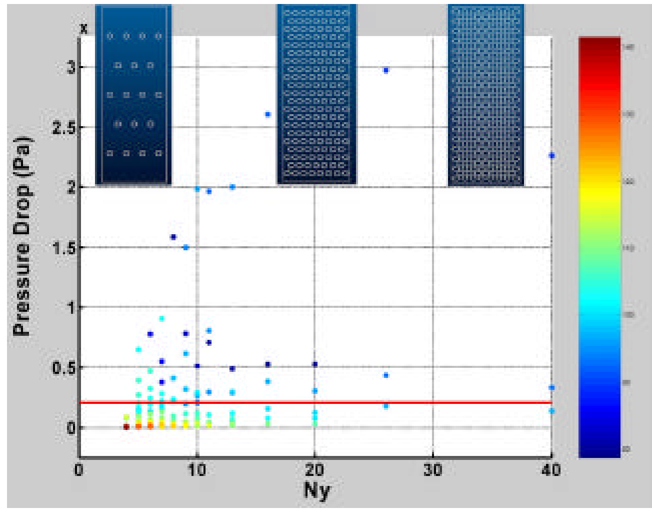

Figure 9 Scatter plot of the pressure drop dP versus the number of pins in the flow direction Ny.

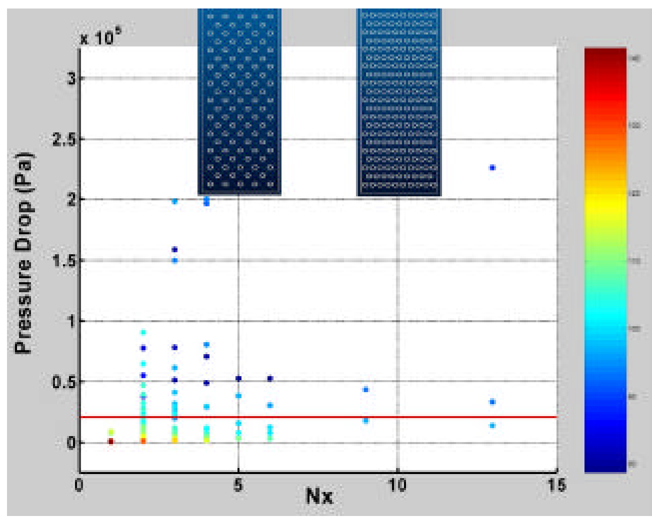

Figure 10 Scatter plot of the pressure drop dP versus the number of pins in the cross flow direction Nx.

(insulated gate bipolar transistor) surface are generated. The values of these analysis features are being used to compute the Reynolds number, the heat transfer coefficient, the pressure drop and the maximum temperature of the IGBT surface. As a designer changes the number of fins he can immediately find the pressure drop and the maximum temperature of the IGBT surfaces.

Furthermore, since the evaluation ("experiment") of the design is simple and fast, design space exploration is feasible. If large numbers of design variables are going to be explored one may utilize the design of experiment capability of behavior modeling to identify the design variables that have the most impact on the performance attributes of the design. Following the identification of the most influential design variables, one can perform a design optimization study. The optimization design study can become a behavioral modeling feature and it will always optimize the design if an independent design variable will be changed. Figure 8 shows the temperature distribution on the IGBT surface generated within the CAD environment.

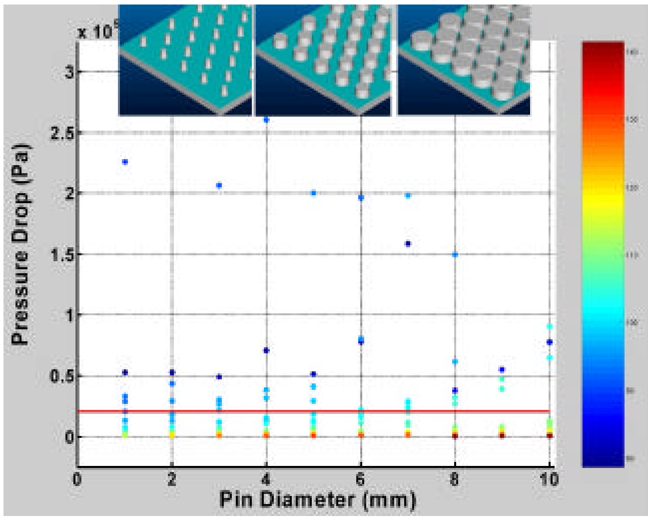

Figure 11 Scatter plot of the pressure drop dP versus the pin diameter Dpin.

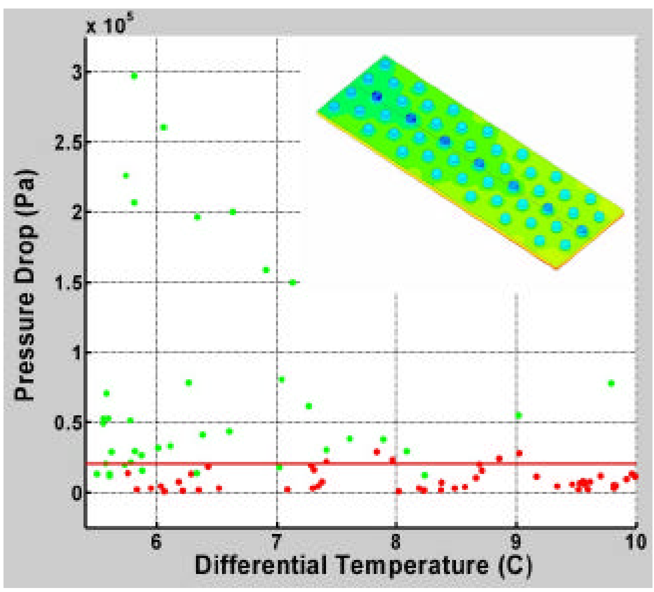

Figure 12 Scatter plot of the pressure drop dP versus th**e** Differential Temperature dT

Multi-objective Design Study

The effect of several design variables on the pressure drop dP and maximum temperature maxT was examined. The design variables considered were the number of pins in the direction of the flow Ny, the number of pins in the direction normal of the flow Nx, the pin diameter Dpin and the pin height Hpin. Since the number of pins Nx and Ny are discrete variables the traditional gradient based optimization algorithms are not successful. Using the design automation steps described in the previous sections one may compute quickly the maximum temperature and pressure drop for a given set of design variables. Figure 9 shows a scatter plot of the pressure drop versus the number of pins in the flow direction. For a given value of Ny there are several design points corresponding to various values of the other design variables such as pin diameter and the number of pins in the cross flow direction Nx. The design points are color coded based on the maximum temperature value. The red horizontal line indicates the pressure drop target. Any design point below the red line meets the pressure drop target. One may easily select any point below the line that meets the maximum temperature target.

Figure 10 shows a scatter plot of the pressure drop versus the number of pins in the cross flow direction. For a given value of Nx there several design points corresponding to various values of the other design variables such as pin diameter and the number of pins in the flow direction Ny. Any design point below the red line meets the pressure drop target. One may easily select any point below the line that meets the maximum temperature target.

Figure 11 shows a scatter plot of the pressure drop versus the pin diameter. For a given value of Dpin there are several design points corresponding to various values of the other design variables such number of pins in the flow direction Ny and the number of pins in the cross flow direction Nx.

Figure 12 shows a scatter plot of the pressure drop versus the differential temperature dT (dt = Tmax - Tmin) at the IGBT surface. The data points have been color coded with respect to the maximum Temperature Target. Red data points correspond to maximum temperature greater than the target and green data points correspond to maximum temperature less than the target. In other words all green points satisfy the maximum temperature constraint and all points below the red horizontal line satisfy the pressure drop target. To select the optimum design point from all the points that satisfy both constraints one can select the point on the left hand side of the plot that minimizes the temperature differential.

Conclusions

The pin-finned design seems the most promising cooling technique that meets the performance criteria for automotive applications.

Integration of behavioral modeling, thermal FEA and multi-objective design exploration techniques empower engineers to rapidly obtain optimum designs of challenging engineering problems.

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